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TECHNICAL REPORT

Establishing RIPDLIPI Lethality Tables for the General Population

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14. ABSTRACT
This report describes the modification of the Radiation-Induced Performance Decrement Lethality Injury Probability Interpolation (RIPDLIPI) 3.0 software to include look-up tables (LUTs) for calculating lethality for general populations. The previous versions of RIPDLIPI were designed to calculate probability of lethality from nuclear fallout for military populations. The current work makes the RIPDLIPI 3.0 software applicable to a wider range of modeling tasks. The new lethality LUTs have the same format as the legacy lethality LUTs and can be used with the existing RIPDLIPI 3.0 software. We discuss the methodology for the creation and verification of these tables, and briefly describe the use of the new tables within the existing HPAC infrastructure.

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RIPDLIPI, HENRE, RIPD, Radiation, Fallout, Lethality

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UNIT CONVERSION TABLE

U.S. customary units to and from international units of measurement[*]

U.S. Customary Units	Multiply by → ← Divide by[†]	International Units
Length/Area/Volume		
inch (in)	2.54 $\times 10^{-2}$	meter (m)
foot (ft)	3.048 $\times 10^{-1}$	meter (m)
yard (yd)	9.144 $\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344 $\times 10^{3}$	meter (m)
mile (nmi, nautical, U.S.)	1.852 $\times 10^{3}$	meter (m)
barn (b)	1 $\times 10^{-28}$	square meter (m^2)
gallon (gal, U.S. liquid)	3.785 412 $\times 10^{-3}$	cubic meter (m^3)
cubic foot (ft^3)	2.831 685 $\times 10^{-2}$	cubic meter (m^3)
Mass/Density		
pound (lb)	4.535 924 $\times 10^{-1}$	kilogram (kg)
atomic mass unit (AMU)	1.660 539 $\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft^{-3})	1.601 846 $\times 10^{1}$	kilogram per cubic meter (kg m^{-3})
Pound-force (lbf avoirdupois)	4.448 222	Newton (N)
Energy/Work/Power		
electron volt (eV)	1.602 177 $\times 10^{-19}$	joule (J)
erg	1 $\times 10^{-7}$	joule (J)
kiloton (kT) (TNT equivalent)	4.184 $\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350 $\times 10^{3}$	joule (J)
foot-pound-force (ft lbf)	1.355 818	joule (J)
calorie (cal) (thermochemical)	4.184	joule (J)
Pressure		
atmosphere (atm)	1.013 250 $\times 10^{5}$	pascal (Pa)
pound force per square inch (psi)	6.984 757 $\times 10^{3}$	pascal (Pa)
Temperature		
degree Fahrenheit (^{o}F)	[T(^{o}F) − 32]/1.8	degree Celsius (^{o}C)
degree Fahrenheit (^{o}F)	[T(^{o}F) + 459.67]/1.8	kelvin (K)
Radiation		
activity of radionuclides [curie (Ci)]	3.7 $\times 10^{10}$	per second (s^{-1}[‡])
air exposure [roentgen (R)]	2.579 760 $\times 10^{-4}$	coulomb per kilogram (C kg^{-1})
absorbed dose (rad)	1 $\times 10^{-2}$	joule per kilogram (J kg^{-1}[§])
equivalent and effective dose (rem)	1 $\times 10^{-2}$	joule per kilogram (J kg^{-1}[**])

[*]Specific details regarding the implementation of SI units may be viewed at http://www.bipm.org/en/si/.

[†]Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

[‡]The special name for the SI unit of the activity of a radionuclide is the becquerel (Bq). (1 Bq = 1 s^{-1}).

[§]The special name for the SI unit of absorbed dose is the gray (Gy). (1 Gy = 1 J kg^{-1}).

[**]The special name for the SI unit of equivalent and effective dose is the sievert (Sv). (1 Sv = 1 J kg^{-1}).

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Acknowledgements

We gratefully acknowledge Dr. Paul Blake and DTRA's Nuclear Technologies Survivability Division for programmatic support; the work was performed under DTRA contract HDTRA1–14–D–0003/0005.

Executive Summary

This report describes the modification of the Radiation–Induced Performance Decrement Lethality Injury Probability Interpolation (RIPDLIPI) 3.0 software to include look–up tables (LUTs) for calculating lethality for general populations. The previous versions of RIPDLIPI were designed to calculate probability of lethality from nuclear fallout for military populations. The current work makes the RIPDLIPI 3.0 software applicable to a wider range of modeling tasks. The new lethality LUTs have the same format as the legacy lethality LUTs and can be used with the existing RIPDLIPI 3.0 software. We discuss the methodology for the creation and verification of these tables, and briefly describe the use of the new tables within the existing HPAC infrastructure.

1 Introduction

This technical report discusses an extension of the Radiation–Induced Performance Decrement Lethality Injury Probability Interpolation (RIPDLIPI) 3.0 software to include probability of lethality for general populations. We provide new look–up tables that are based on a radiation lethality model that uses a global age–weighted LD_{50} (Wilkinson et al., 2017; Stricklin et al., 2017. The new LUTs have the same format as the original RIPDLIPI 3.0 LUTs and can be used in place of those tables by the existing RIPDLIPI 3.0 software distribution. Previously, it was only possible to calculate lethality in RIPDLIPI for military age populations, because the LUTs were created with an LD_{50} value for that population.

The new LUTs were created using a plugin to HENRE (Health Effects from Nuclear and Radiological Environments; (Oldson et al., 2017). HENRE includes an implementation of (1) a prompt dose radiation lethality probit model, and (2) the MARCELL cell kinetics model (Jones et al., 1991), the models upon which the legacy RIPDLIPI lethality tables were based. Using HENRE,

- the MARCELL model was integrated to describe bone marrow cell injury and death associated with exposure to a time–dependent radiation dose rate $R(t)$ (described below),
- using MARCELL, the maximum bone marrow cell death was estimated,[1] and
- an equivalent prompt dose was estimated based on the degree of cytopenia (i.e., a prompt dose that would produce the same cell death maximum).

This equivalent prompt dose was used with the aforementioned prompt dose radiation lethality probit model to determine probability of lethality at 60 days, based on experimentally established LD_{50} and probit slope. When the legacy RIPDLIPI tables were created, the LD_{50} for military aged males was used (Anno et al., 2003); in this work we also use a global age–weighted LD_{50}. More information on the HENRE models is available in the HENRE Technical Reference Manual (Oldson et al., 2017).

As described above, recent work (Stricklin et al., 2017) has offered the opportunity to extend the range of RIPDLIPI to the general population. Stricklin reviewed the available data on the variability in response to radiation among several animal species at different ages of exposure. The animal data were categorized by age groups corresponding to physiological and developmental stages and these categories were used to extrapolate to expected response in humans. In this way LD_{50} values for a set of 5 human age groups (Infant, Juvenile, Adult, Late Adult, Elderly) were obtained. These individual LD_{50} values were used to estimate a globally age–weighted LD_{50} (Wilkinson et al., 2017) using the ORNL global age–distribution database (Bright et al., 2016). The new values are shown in Table 1.1. We have used this globally age–weighted value for LD_{50} with the HENRE radiation lethality model to create the new RIPDLIPI tables.

[1] A key assumption of the MARCELL model is that cytopenia of a critical bone marrow cell determines lethality

Table 1.1: LD_{50} Estimates for five age groups

Age Category	**Global Distribution (%)**	**LD_{50} (Gy)** (free in air)
Infant	1	3.28
Juvenile	24	3.53
Adult	50	4.1
Late Adult	15	3.53
Elderly	9	2.91
General Population	100	3.75

The next section gives details on the methodology used to create the RIPDLIPI tables, and Section 3 describes the verification of the tables and gives a brief discussion of their implementation within HPAC.

2 Methods

As discussed above, HENRE includes an implementation of the MARCELL cell kinetics model (Jones et al., 1991), a key component of HENRE's model of lethality from protracted radiation exposure (which is a new implementation of the radiation lethality model in RIPD). The MARCELL model takes as input gamma ray and neutron dose rate functions. HENRE then solves MARCELL's coupled differential equations to describe bone marrow cell injury and death. HENRE then estimates an equivalent prompt dose (EPD) based on the degree of cytopenia, and the EPD is used in a prompt dose radiation lethality probit model to determine probability of lethality at 60 days.

The original impetus for the creation of RIPDLIPI was to improve the performance of RIPD in time–critical situations. Specifically, RIPDLIPI was designed to ingest output from the HPAC transport–dispersion model known as SCIPUFF (Second Order Closed Integrated Puff). Within HPAC, SCIPUFF calls RIPDLIPI for each spatial grid cell computed during the dispersion. A typical HPAC run can involve thousands or tens of thousands of calls to RIPDLIPI for lethality calculations (Crary et al., 2015), and the time required to integrate the HENRE equations in these situations is prohibitive for real–time operation.

RIPDLIPI contains a LUT of lethality values calculated with HENRE on a logarithmic grid and implements an interpolation method for calculating lethality for arbitrary input values, thus providing improved performance for computationally intensive applications. The inputs required by the interpolation function for the RIPDLIPI tables are the dose rate at entry (DRE) to the fallout field (cGy/h), the age of the fallout field at entry (AGE; hours), and the duration of the exposure (DUR; hours). These parameters are shown schematically in Figure 2.1. The range of validity of these inputs is given in Table 2.1. HENRE calculations for the look–up tables are based on exposure to a $t^{-1.3}$ decay field, where t is the time elapsed since detonation. This is the characteristic dosage received from fallout after a nuclear detonation. The exact form of the fallout field dose rate function $R(t)$ input to MARCELL

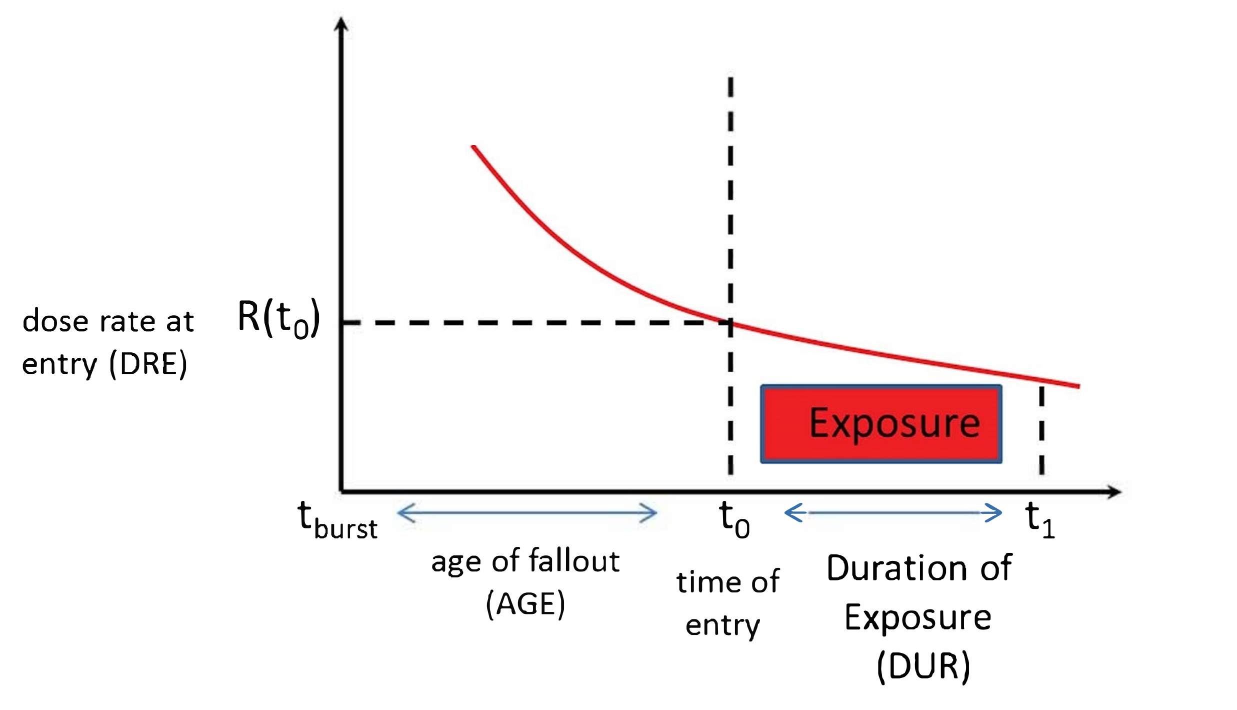

Figure 2.1: Parameters used by RIPDLIPI to define a fallout field: DRE, AGE, DUR.

Table 2.1: Input Parameter Ranges for RIPDLIPI LUTs

Parameter	**Minimum**	**Maximum**
Age of Fallout at Entry (h)	0.01	10,000
Dose Rate at Entry (cGy/h)	0.1	100,000
Duration of Exposure (h)	0.1	5,000

in HENRE for the lethality table calculations is given by:

$$R(t) = (DRE/AGE^{-1.3})(t - t_0 + AGE)^{-1.3}$$

where the parameter definitions are given in Figure 2.1.

As can be seen in Table 2.1, the maximum duration of exposure in RIPDLIPI is 5000 hours (approximately 200 days; this was a user requirement when RIPDLIPI was originally developed). However, RIPDLIPI output for all values of duration of exposure is considered to be probability of 60–day lethality: owing to the $t^{-1.3}$ decay of the radiation field, for large values of t the effects of fallout exposure on lethality are minimal.

HENRE models the effects of radiation shielding (e.g., from entering a building or vehicle) using a simple protection factor PF, where PF > 1 (doses and dose rates are divided by PF). The original implementation of RIPDLIPI created separate LUTs for each protection factor

Table 2.2: RIPDLIPI Protection Factors Values

Protection Factor Number	**Posture**	**Protection Factor Value**
0	In the Open	1.4
1	Single Story Structure Urban	5
2	Multi–Story Structure Urban	50
3	Basements Urban	30
4	Deliberate UG Shelters Urban	200
5	Expedient UG Shelters Urban	80
6	Single Story Structure Rural	3
7	Multi–Story Structure Rural	10
8	Basements Rural	15
9	Deliberate UG Shelters Rural	100
10	Expedient UG Shelters Rural	80

in HPAC (see Table 2.2). To maintain compatibility with RIPDLIPI 3.0 we have also created a lethality LUT for each of these protection factors. The values of the original protection factors used by HENRE for creating the 11 RIPDLIPI LUTs are given in Table 2.2, along with the indices (0–10) used within RIPDLIPI to identify a particular table, and a brief description of the associated posture. These data are taken from a recent ARA Technical Report (Dant et al., 2018).

To generate a LUT, a 3–dimensional grid of input values (the Cartesian product of DRE, AGE and DUR values) is created as described below, and HENRE is called within a looping structure for inputs corresponding to all possible grid points. The calculated values of the probability of lethality are written to a LUT file; the format of this file is also described below. This procedure is repeated for each protection factor, where the value of the DRE at a particular grid point is decreased by the protection factor before being input to HENRE.

Using the minimum and maximum values listed above, the age of the fallout (AGE) and DRE cover six logarithmic intervals, with 10 logarithmically equidistant grid points per interval, giving 61 grid points, while the duration of exposure covers 48 grid points. In practice, the legacy RIPDLIPI program used a cubic spline interpolation which required an additional grid point outside the active limits of the LUT. This gives a LUT size of $63 \times 63 \times 50 = 198,450$. For compatibility with the earlier RIPDLIPI versions, RIPDLIPI 3.0 also uses the same sized LUTs, though in practice, because of a change in interpolation methods for this version, the extreme values for each input variable are not used (Crary et al., 2015).

The LUTs are stored as text files with 198,450 rows, one row for each LUT entry. The LUT files are named `lethal0.dat`–`lethal10.dat` according to the protection factor number given in the first column of Table 2.2. The arrangement of the values in the text file is such that, using programming terminology for the layout of a 3–dimensional array, the time of duration (DUR) is the major index, followed by the DRE, followed by the AGE. In other words, the first 50 entries in the table are the 50 lethality values associated with the set of DUR values for DRE and AGE at their minimum values. The next 50 entries are the lethality values associated with the set of DUR values for DRE at its second lowest value, and AGE at its lowest value, and so forth.

The computations were done using an "R" (statistical software package) interface to HENRE and the knitr (Xie, 2014) package to document the procedure and provide a platform to ensure reproducible results. To increase performance, calculations were done in parallel on a 8 core processor using the Parallel Virtual Machine (PVM) software version 3.4.5+6. The calculations described below were performed using the "RIPD 5.2 Research" plugin with the HENRE engine rev. 88.

3 Results and Conclusions

The purpose of this work is to extend the applicability of the RIPDLIPI lethality tables to general populations. However, to verify the implementation of the global age–weighted radiation lethality probit model in HENRE, we first recreated the RIPDLIPI lethality tables for military aged populations, using the LD_{50} value in Table 1.1 corresponding to 'adult' populations.

To compare the legacy tables with the HENRE–based tables, histograms were created of the absolute value of the difference between the individual elements in the arrays for each protection factor. In addition, scatterplots were created to show the differences in the LUT values. These plots are shown in Figures 3.1–3.22. Table 3.1 shows a number of quantities calculated from the LUT difference values.

As described above, each RIPDLIPI LUT contains 198,450 entries. Most of the difference values are contained in the first two bins of the histogram. This corresponds to a percentage difference of less than 0.2% between the value in legacy tables and the tables created using HENRE.

The histograms have been truncated on the y–axis at a value of 2000 to show the distribution at higher values of $|P_L^{legacy} - P_L^{AdultMale}|$ more clearly. The histograms and scatter plots show very good agreement between the legacy tables and the tables created with HENRE. From Table 3.1, the fraction of LUT values with differences $> 2\%, 5\%$, and 10% are approximately $1.0\%, 0.5\%$, and 0.1%, respectively.

It should be noted that the Protection Factor Value for Protection Factor 5 ('Expedient UG Shelters Urban') and Protection Factor 10 ('Expedient UG Shelters Rural') are the same, so that the LUT tables generated by HENRE are identical in this case. This is also true for the legacy tables.

We then generated new tables based on HENRE's general population (global age–weighted) 60–day radiation lethality model (Oldson et al., 2017). The relationship between the lethality values calculated for military populations and civilian populations is shown in Figure 3.23. This plot essentially is the same for all protection factors. The global averaged populations show increased lethality at all insult levels, as would be expected because of the decreased LD_{50} levels in the general population. This difference is approximately 10.5% at a probability of lethality of 50% for the military population, decreasing to 5.5% at the corresponding 10% lethality and 3.9% at 90% lethality.

Because of the excellent agreement between the legacy RIPDLIPI tables and the HENRE–

derived tables calculated for military populations, we are reasonably confident that HENRE's global age–weighted radiation lethality probit model has been implemented correctly. The methodologies are the same for both military and age–weighted calculations, only the LD_{50} value used to estimate lethality has changed.

The tables for the general population described here will be implemented as a patch for HPAC 6.5, and the user will be able to switch between the legacy RIPDLIPI 3.0 tables and the new tables for calculations of lethality in civilian populations. In the HPAC 6.5 initial release, the user may select between RIPDLIPI tables for military aged populations, or a new methodology where only the `lethal0.dat` table is used (Dant et al., 2018), and protection factors are calculated dynamically based on known land usage and building types. However, the patch for the global population–averaged LUTs will contain the LUTs for each protection factor, for compatibility with the legacy application.

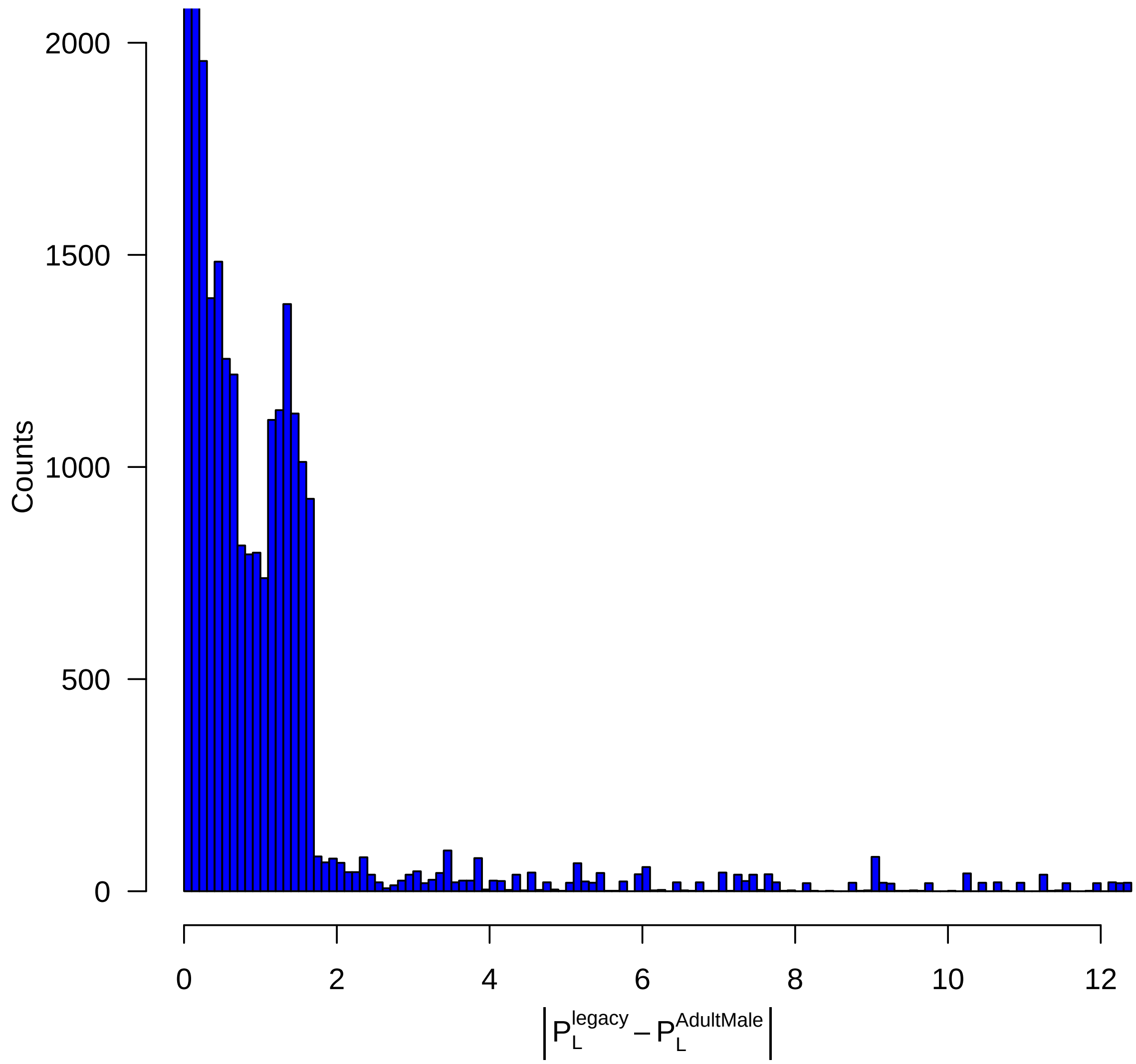

Figure 3.1: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 0

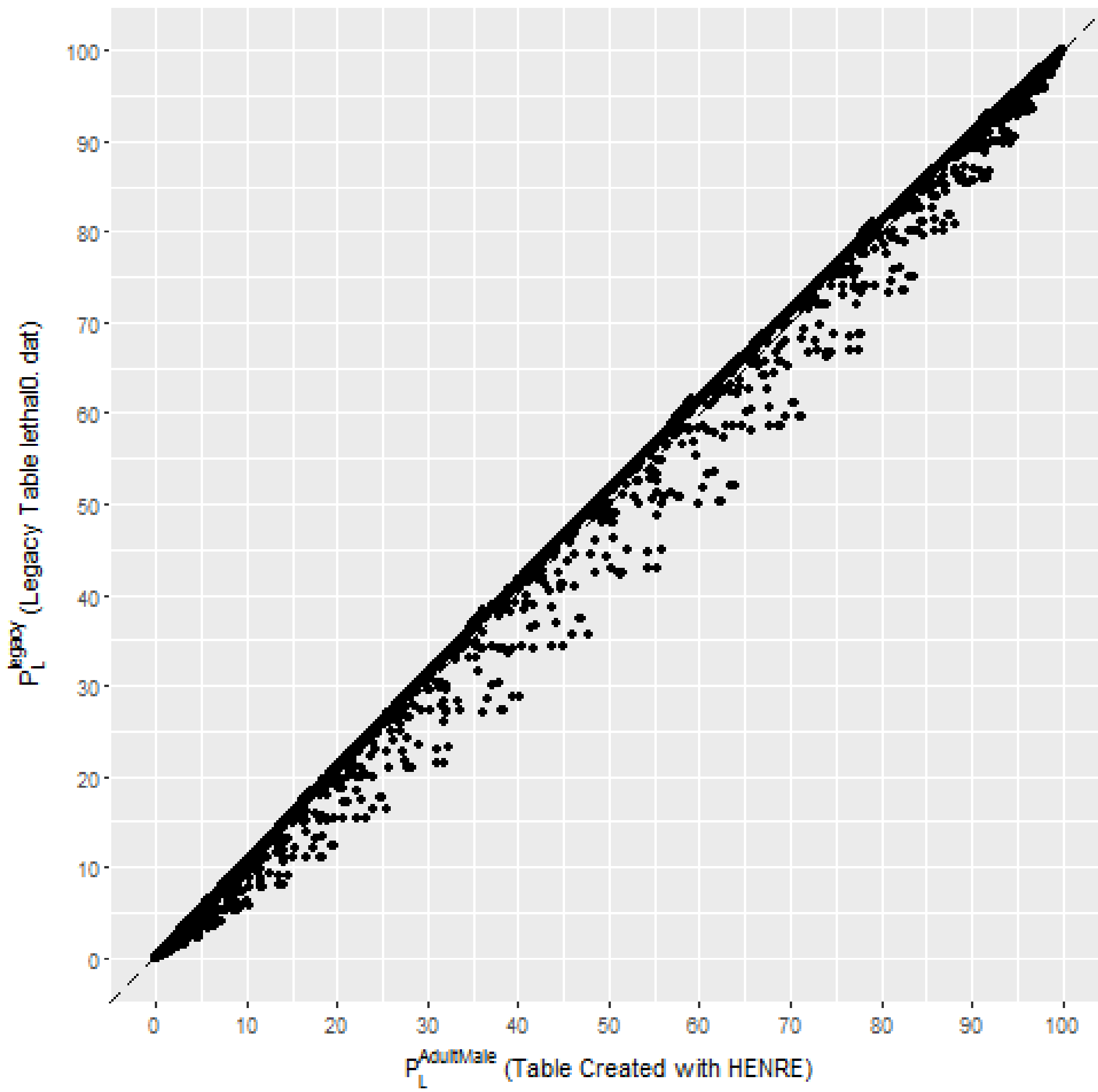

Figure 3.2: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 0

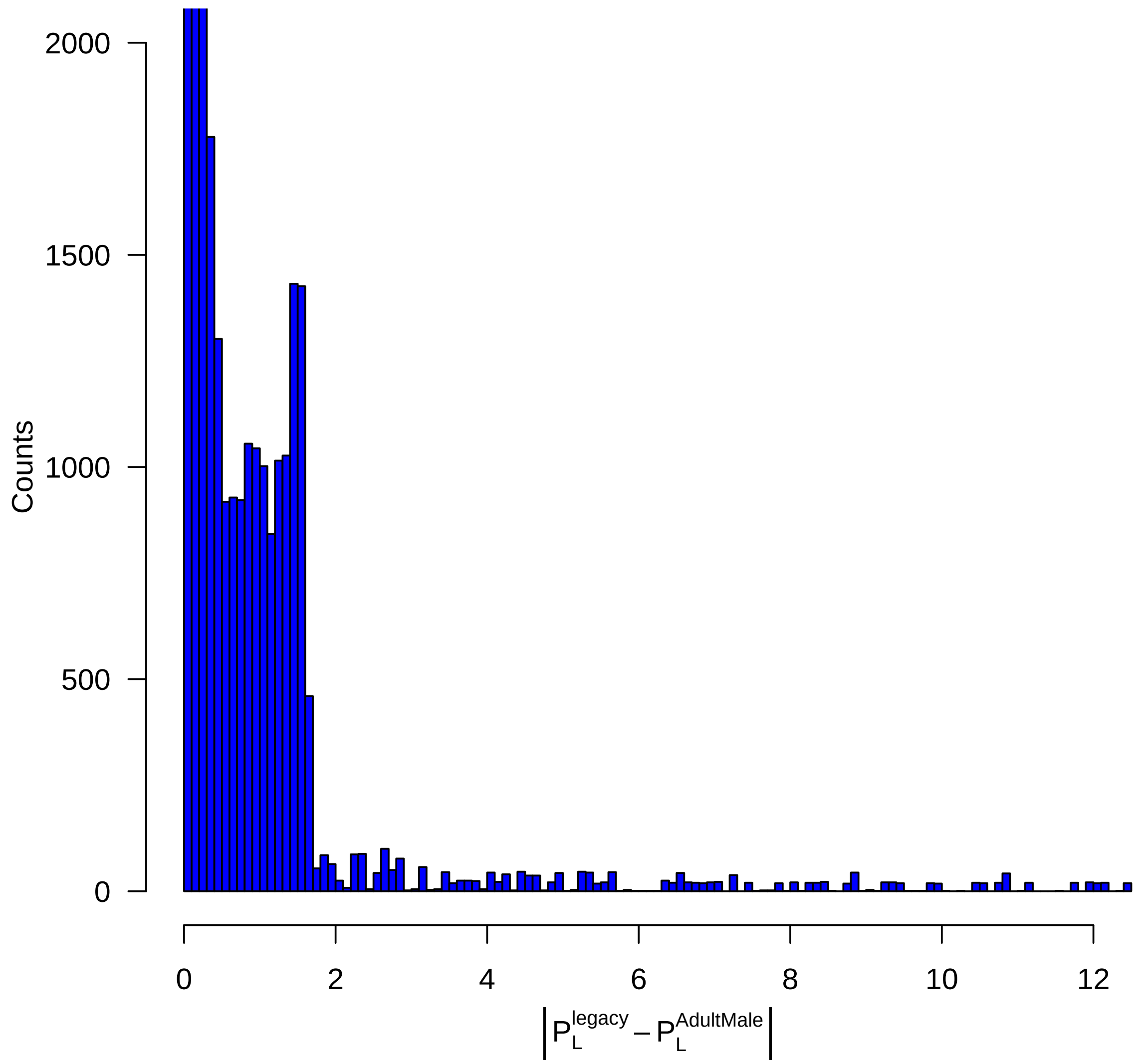

Figure 3.3: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 1

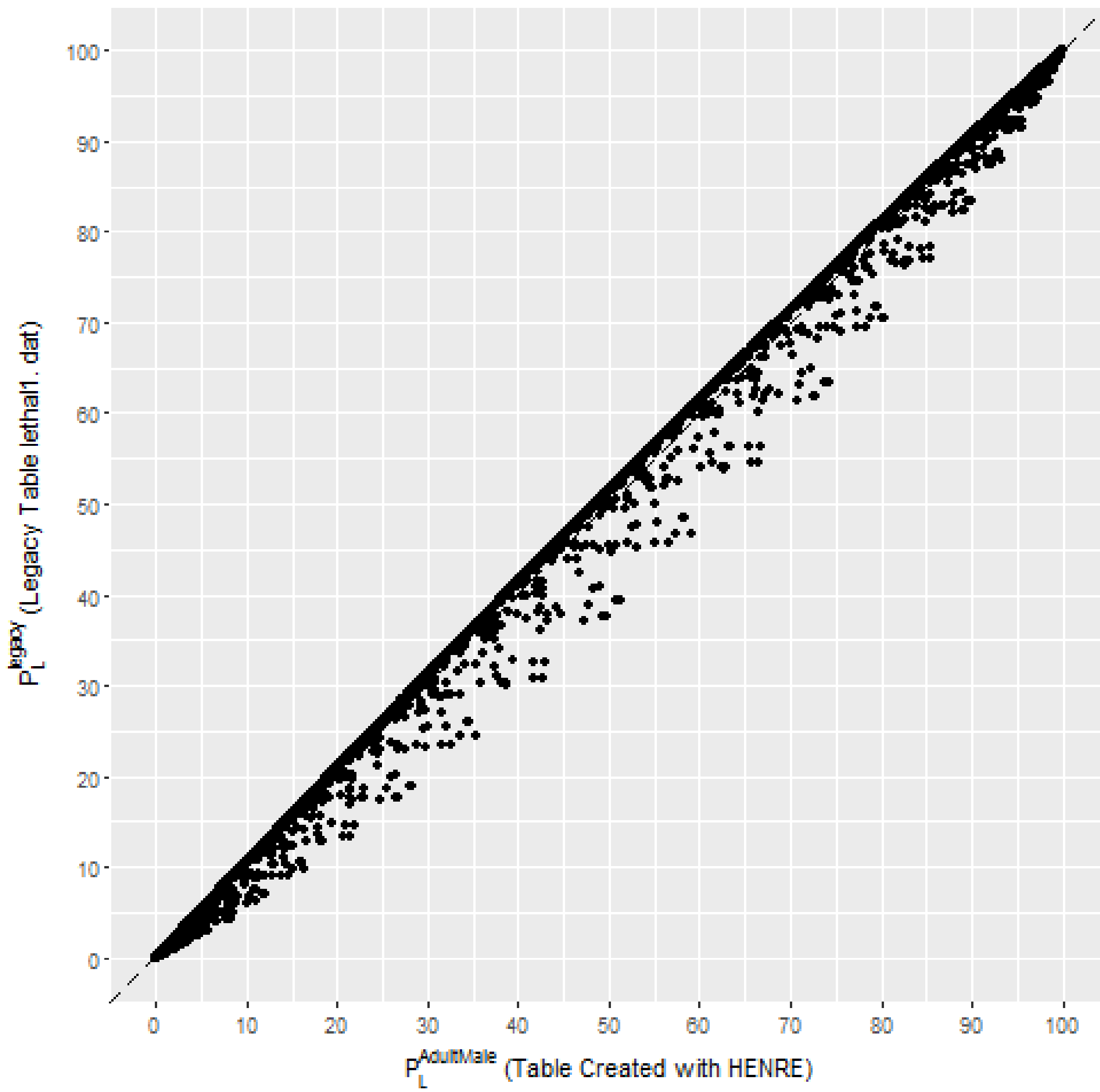

Figure 3.4: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 1

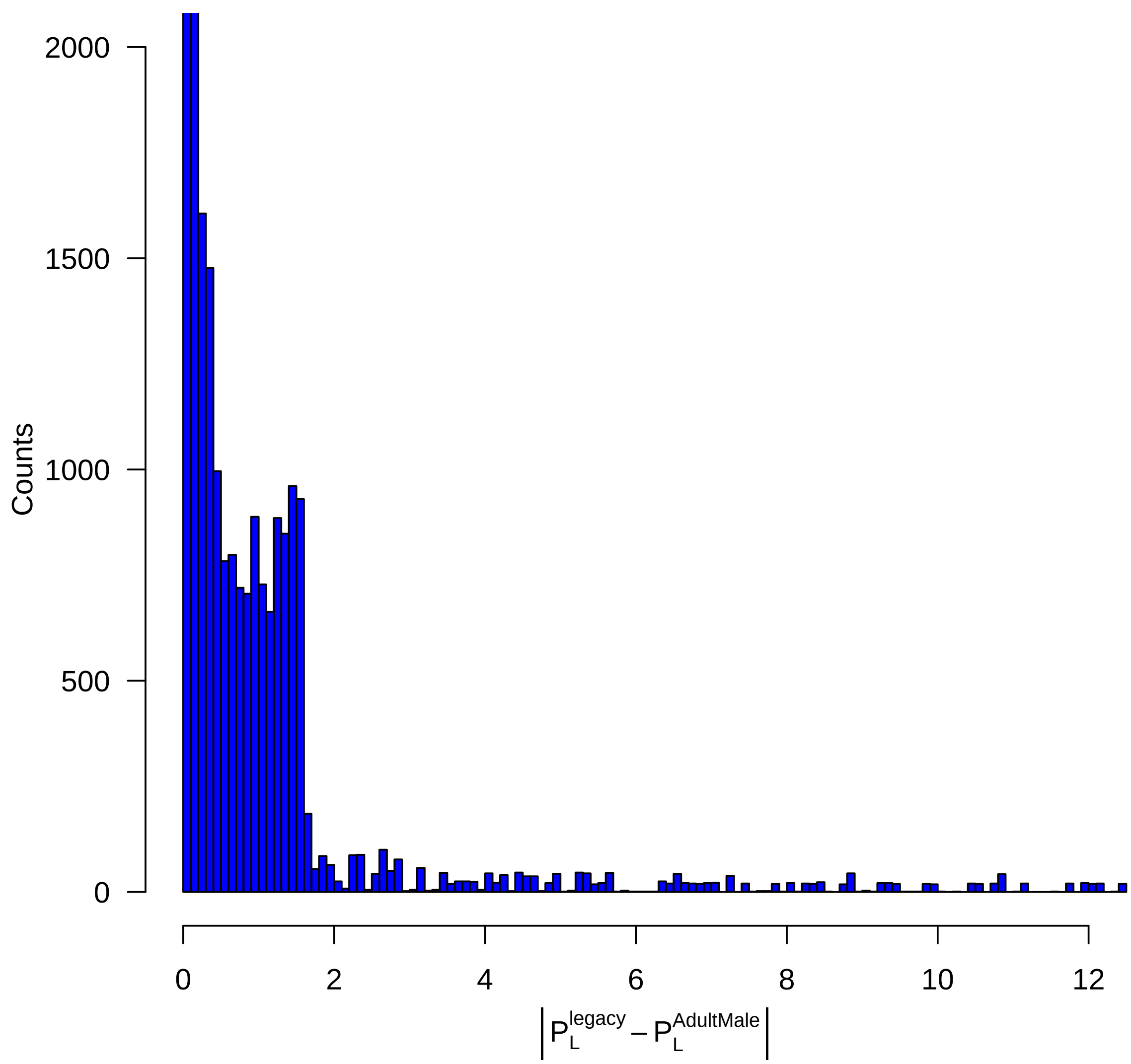

Figure 3.5: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 2

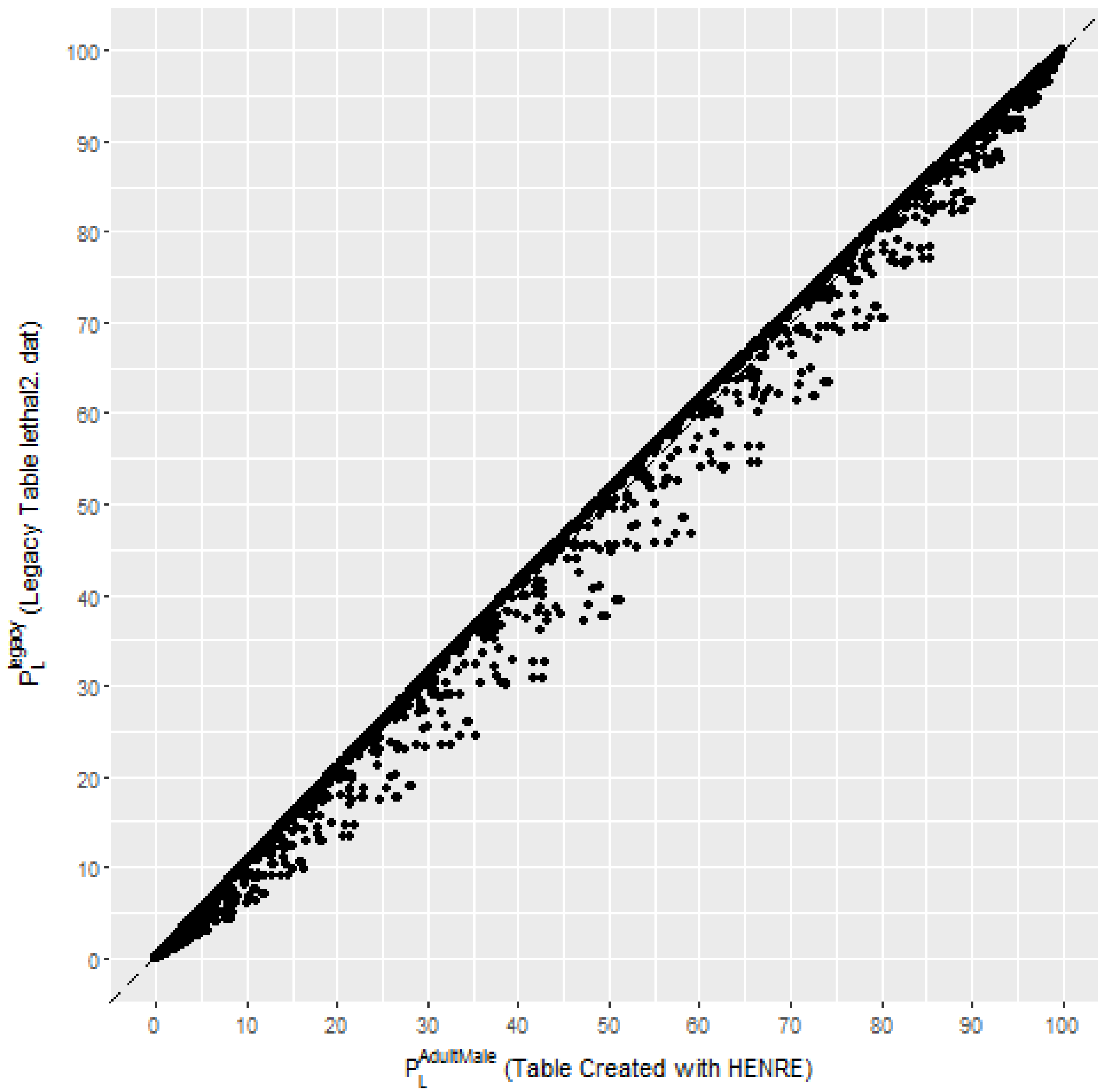

Figure 3.6: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 2

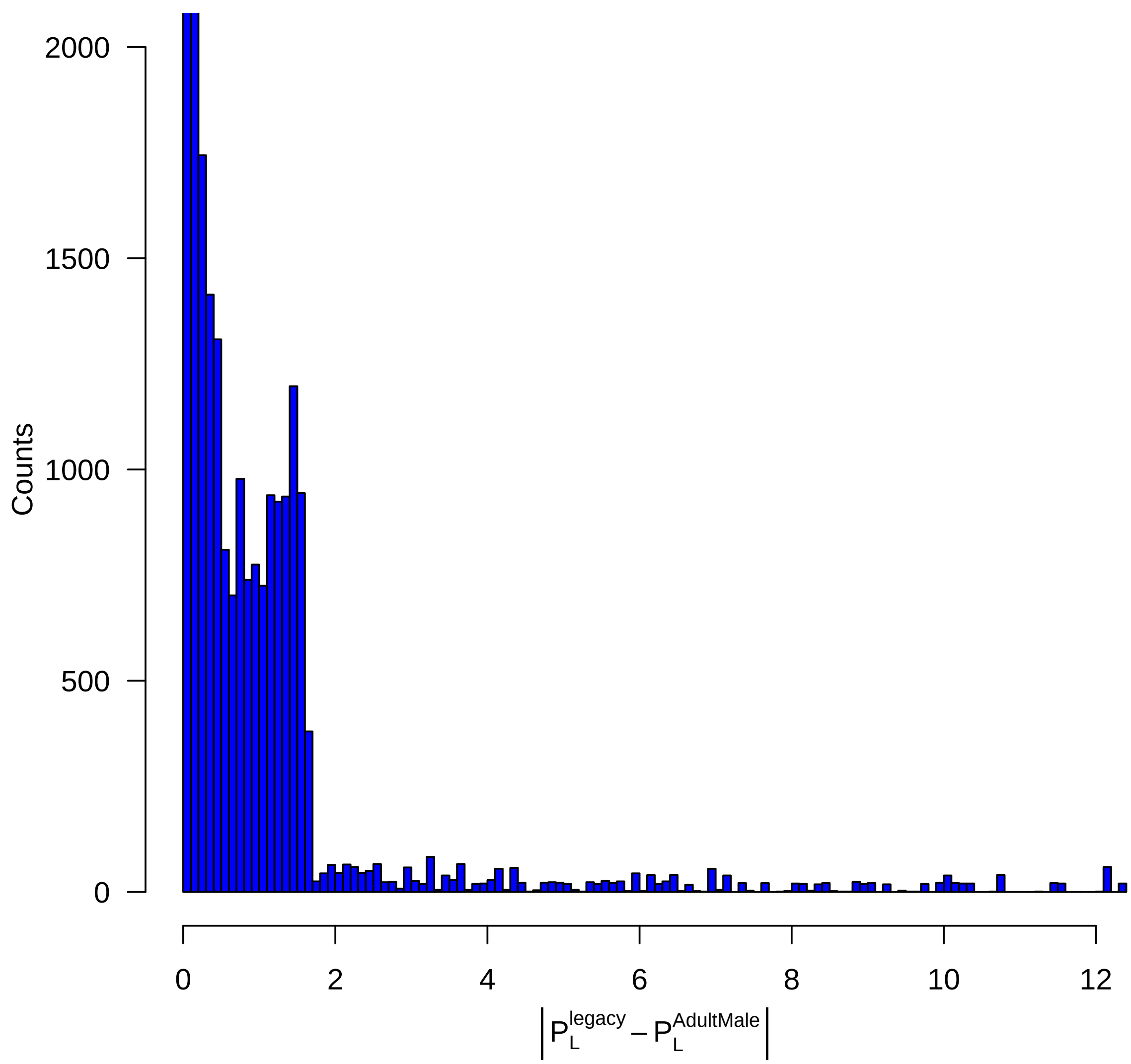

Figure 3.7: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$), protection factor 3

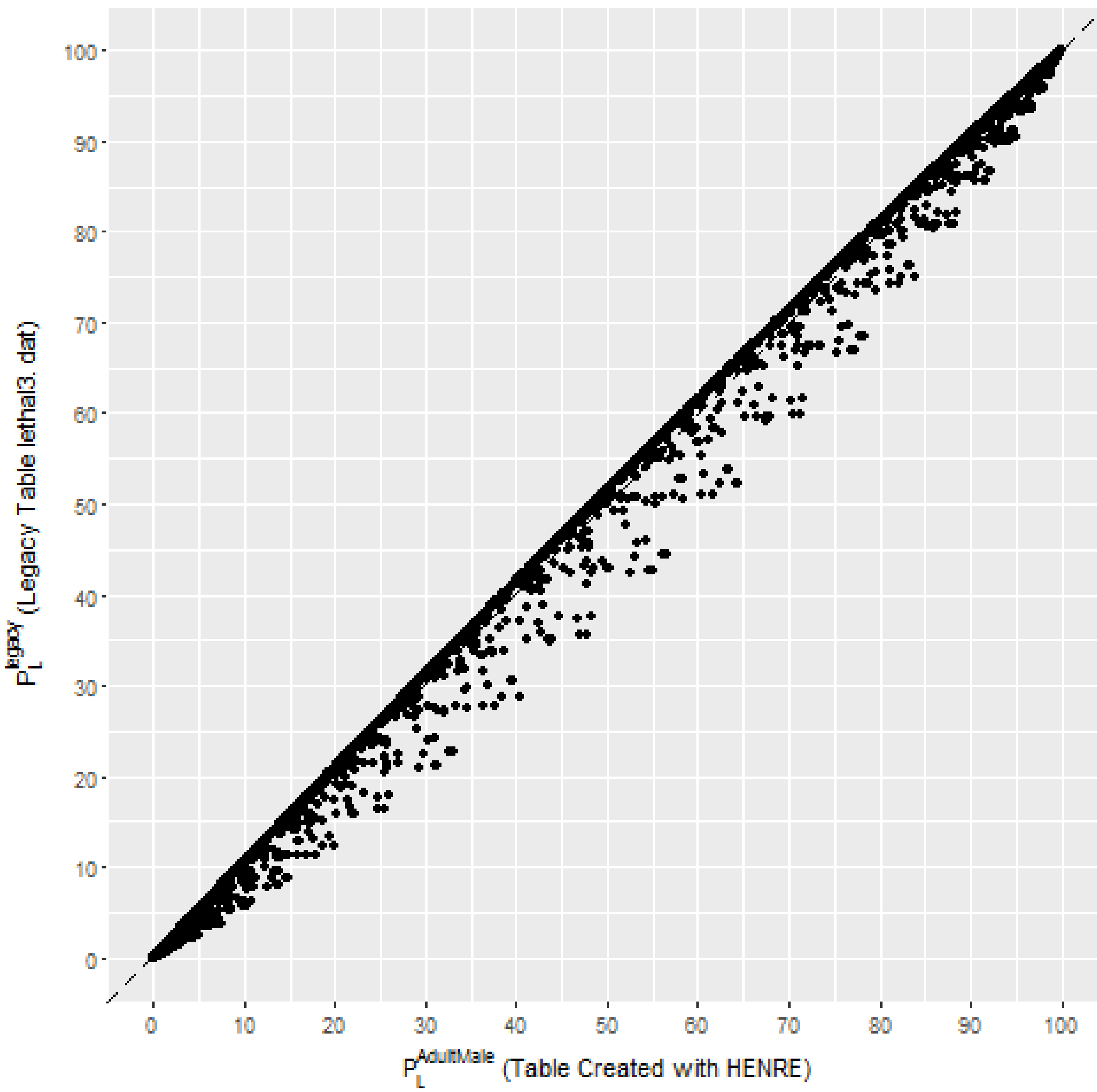

Figure 3.8: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 3

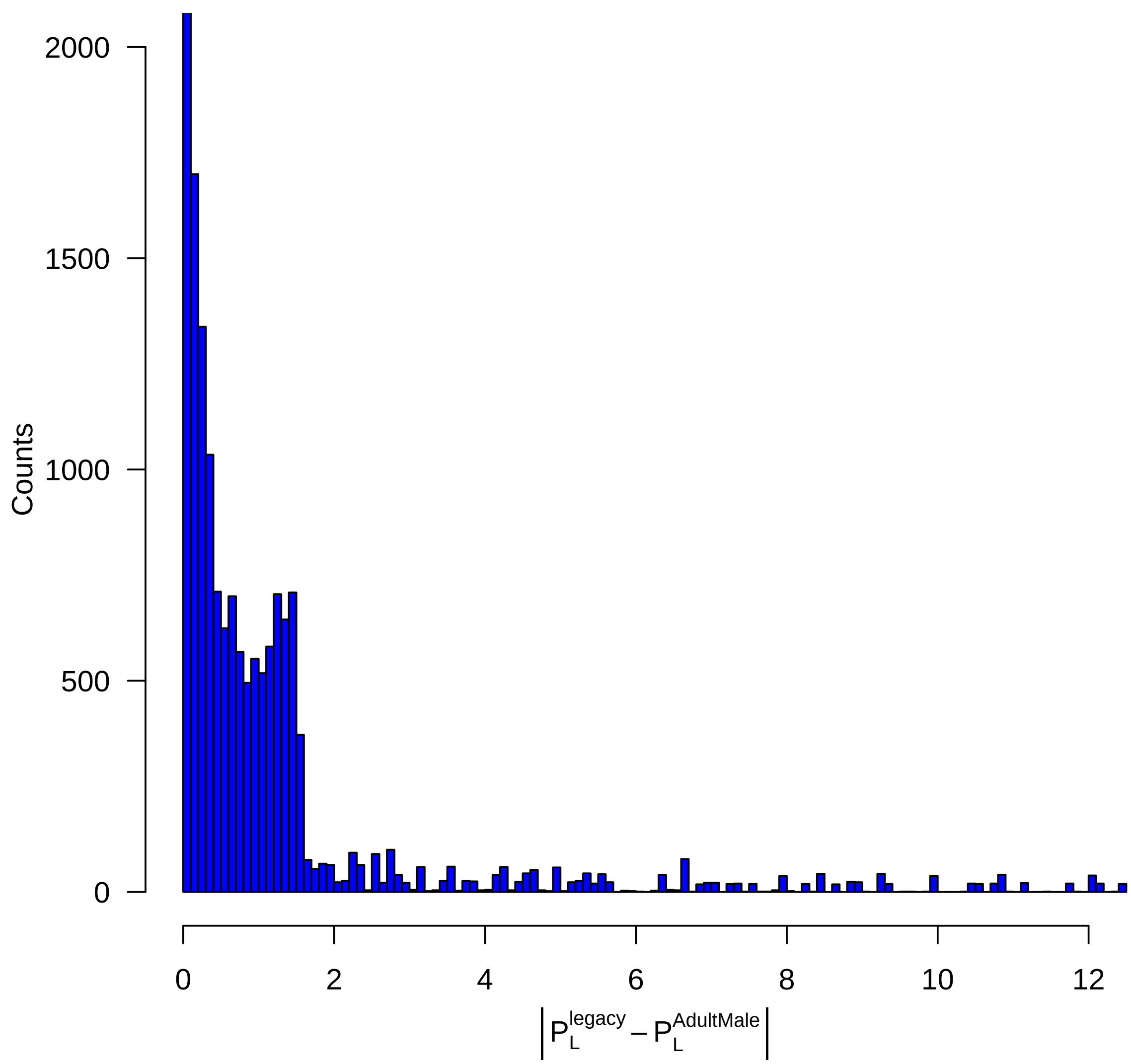

Figure 3.9: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$), protection factor 4

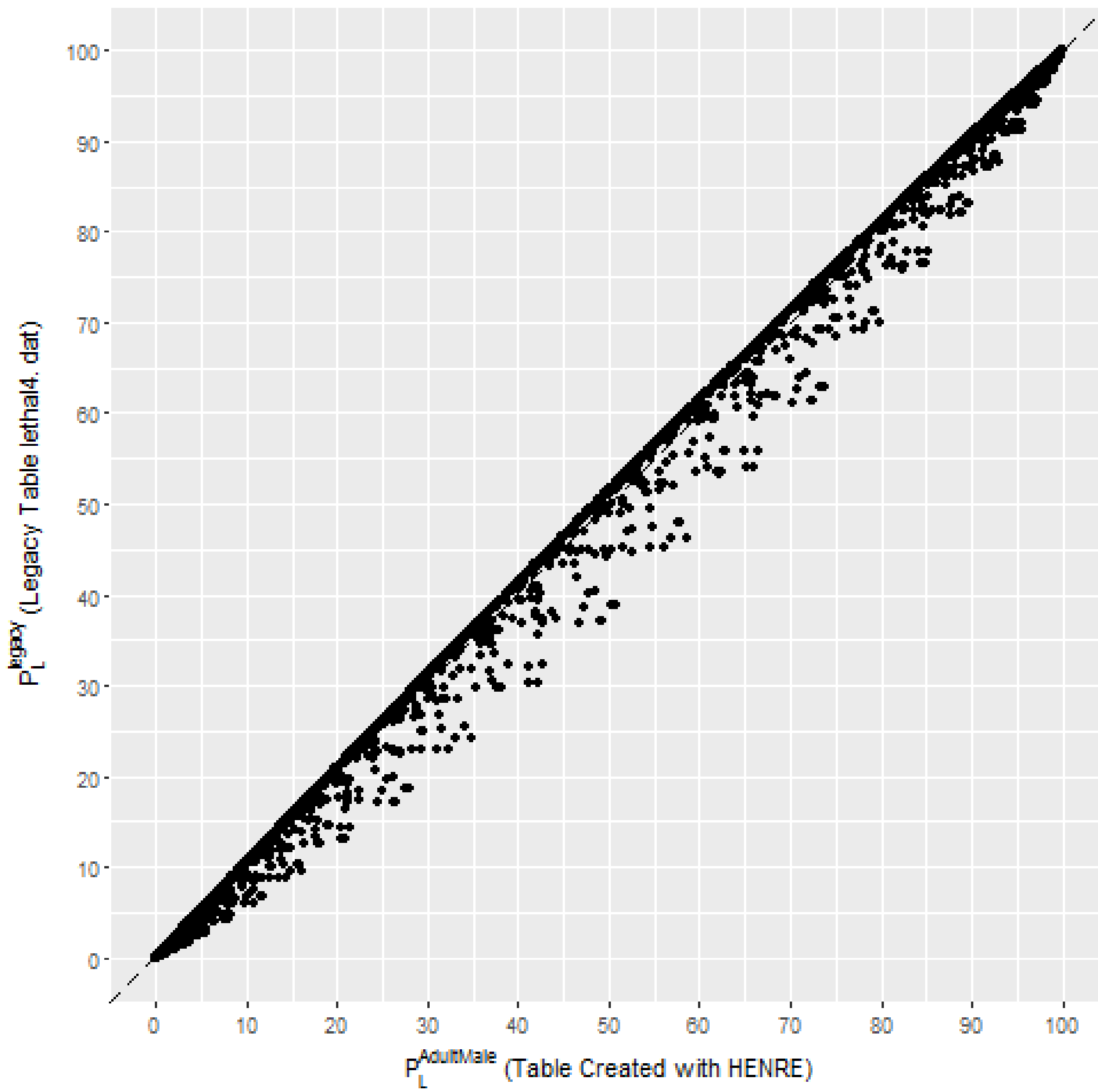

Figure 3.10: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 4

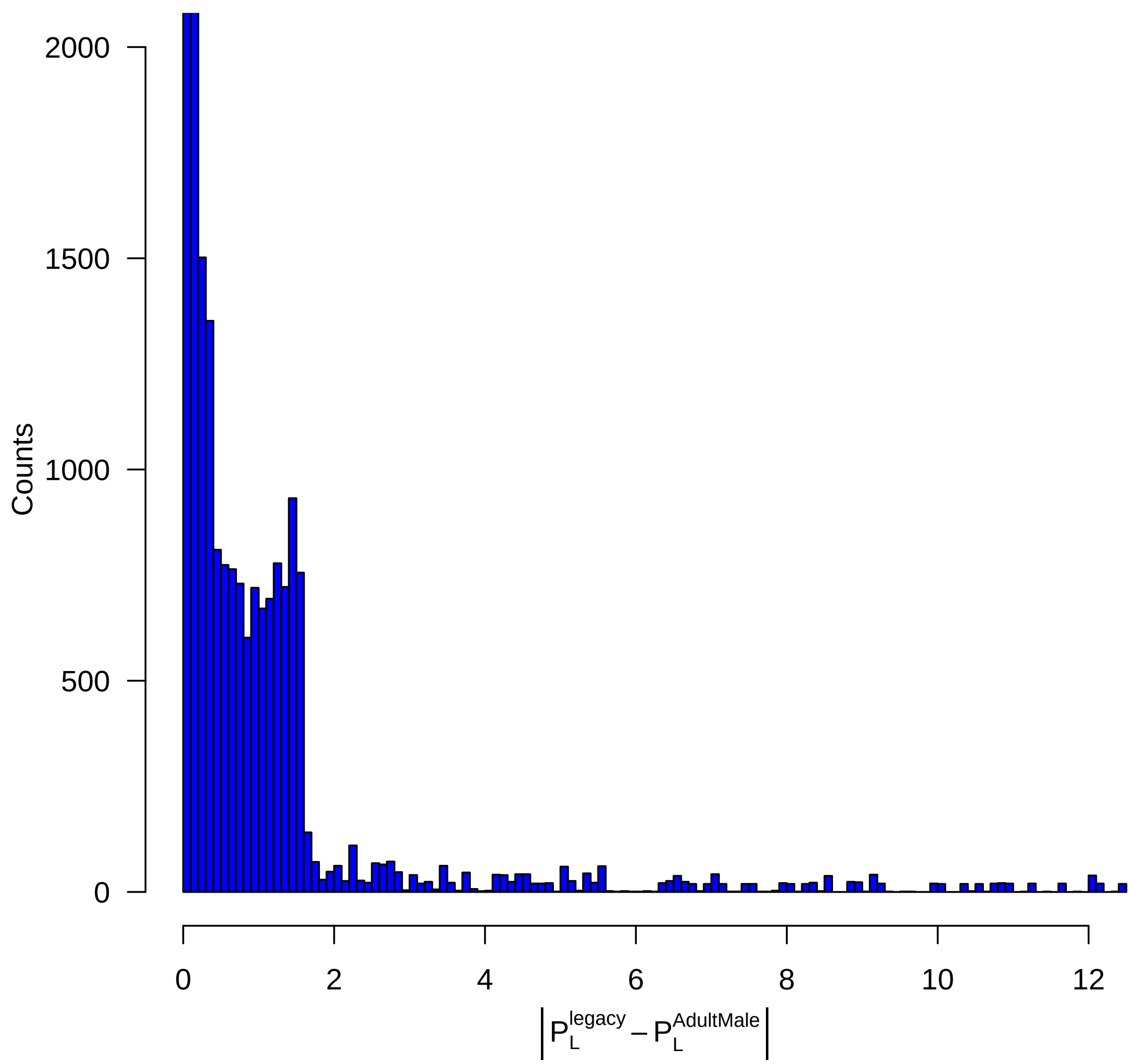

Figure 3.11: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$), protection factor 5

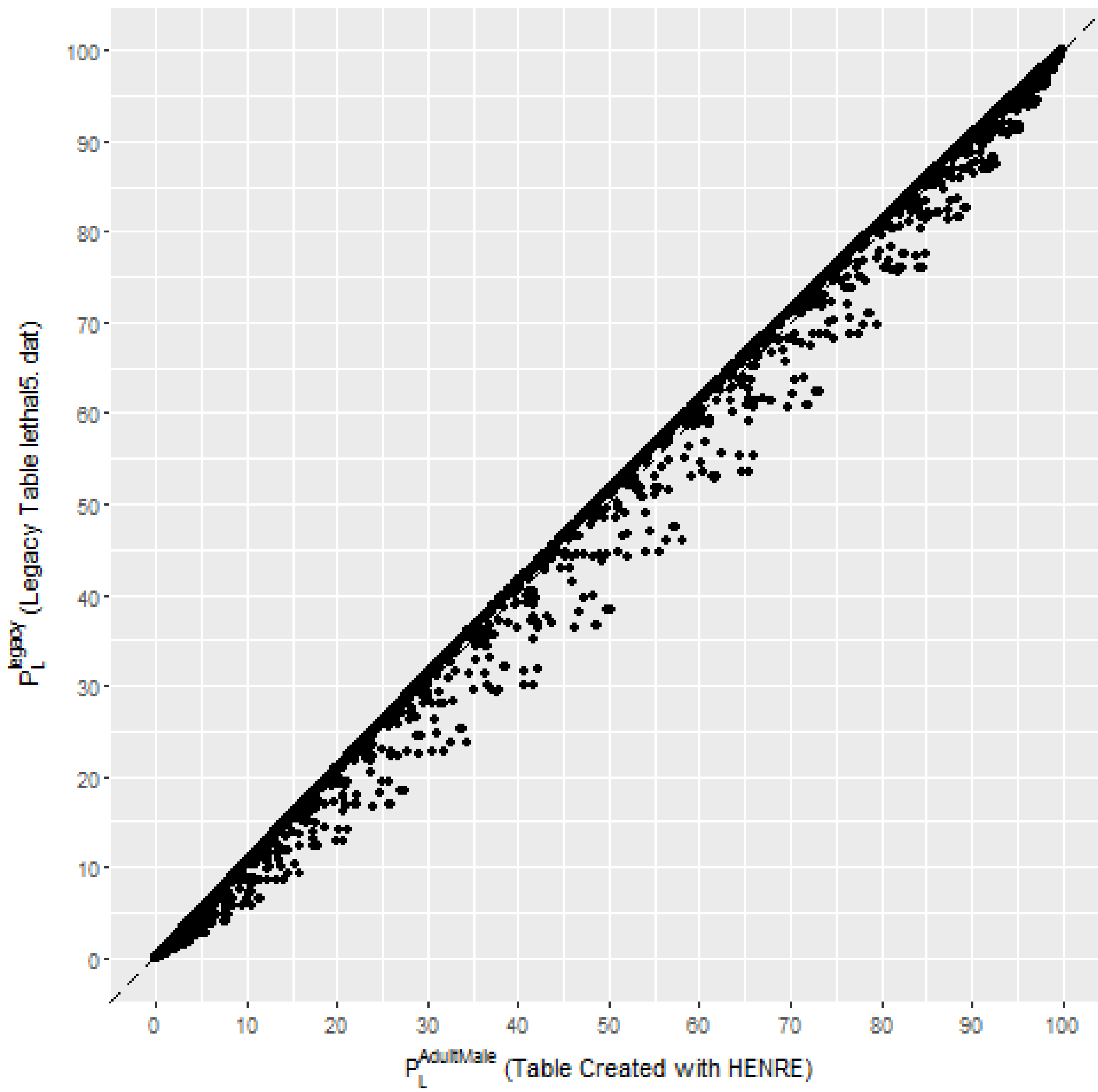

Figure 3.12: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 5

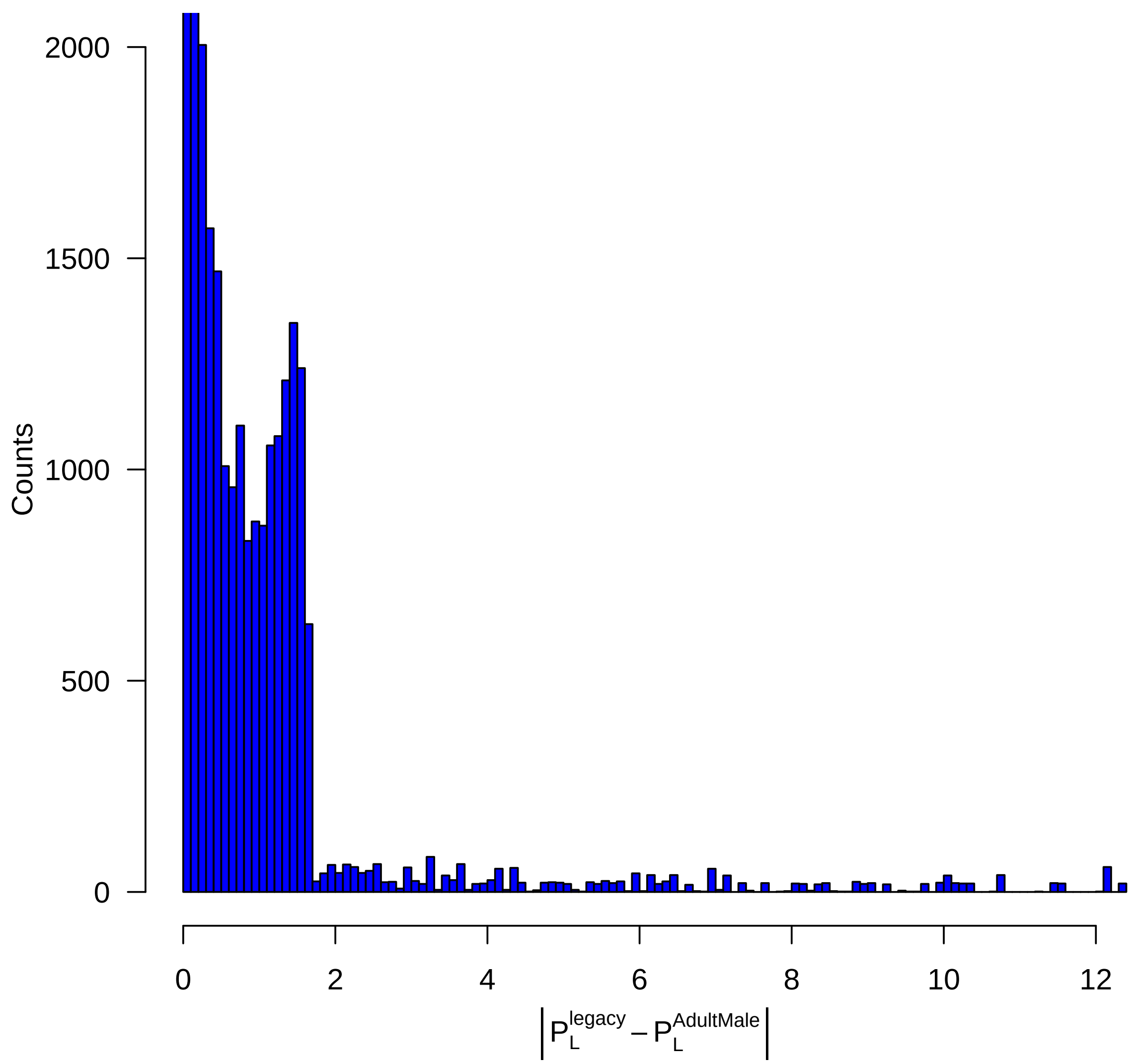

Figure 3.13: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$), protection factor 6

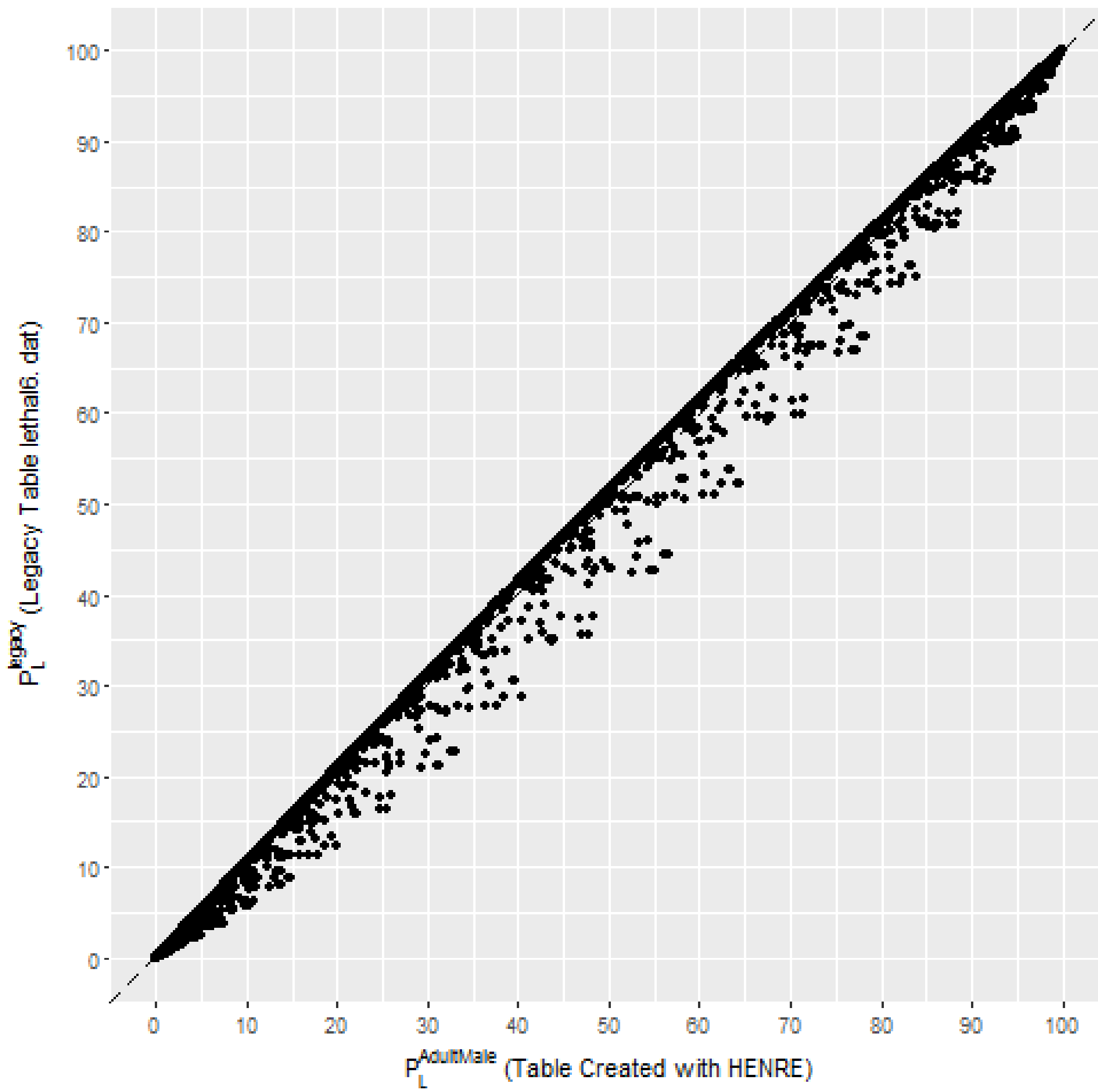

Figure 3.14: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 6

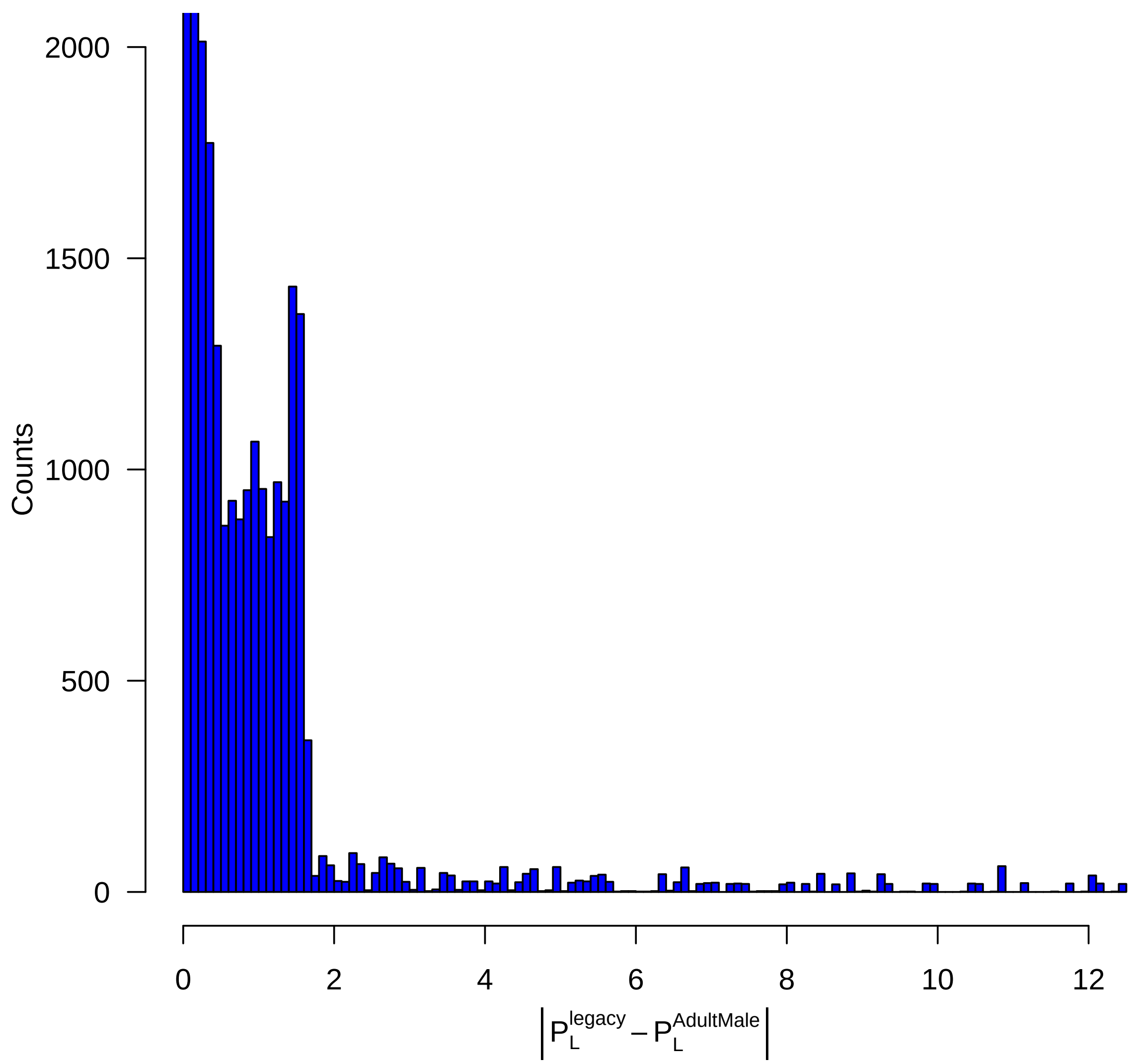

Figure 3.15: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$), protection factor 7

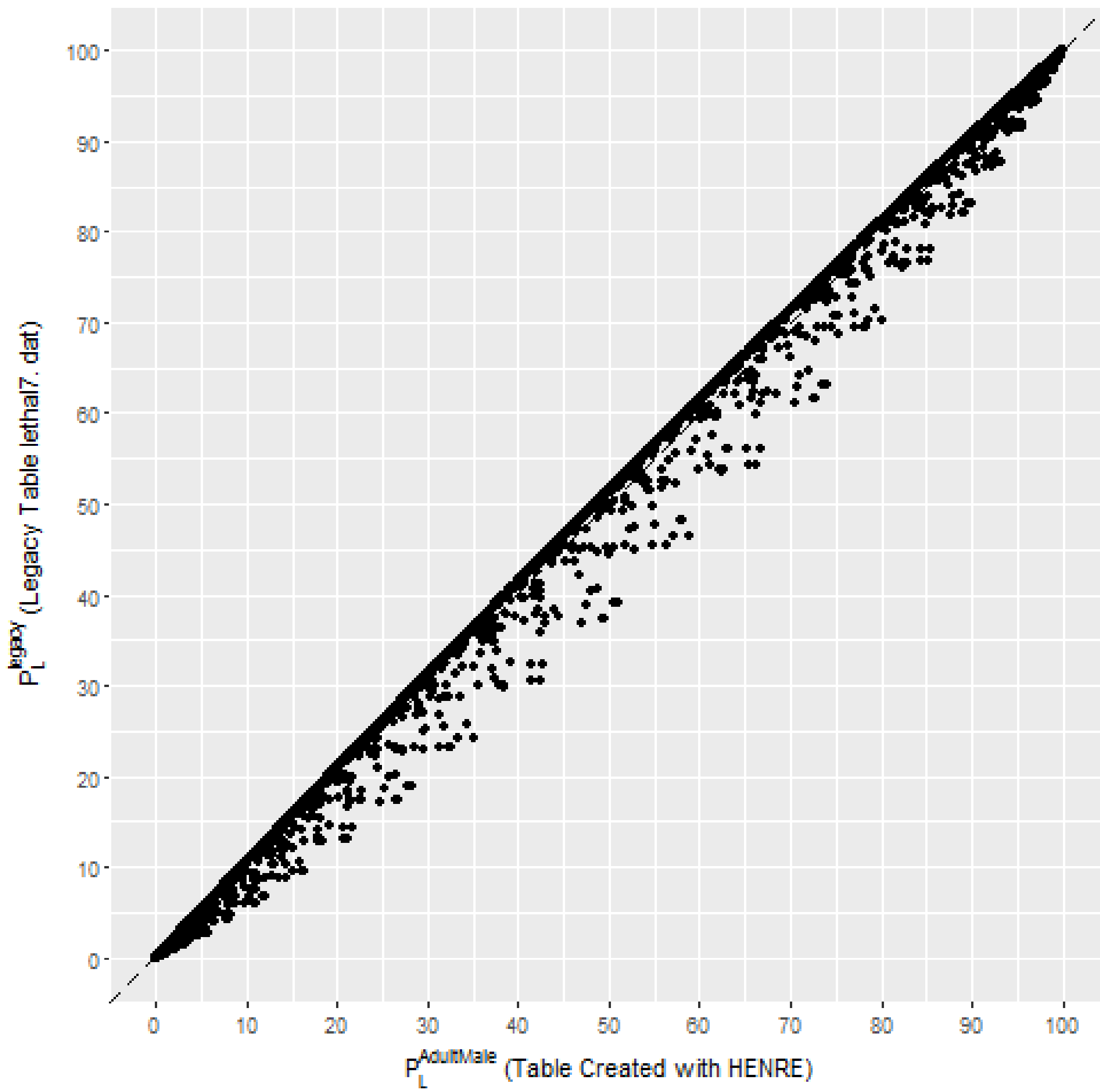

Figure 3.16: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 7

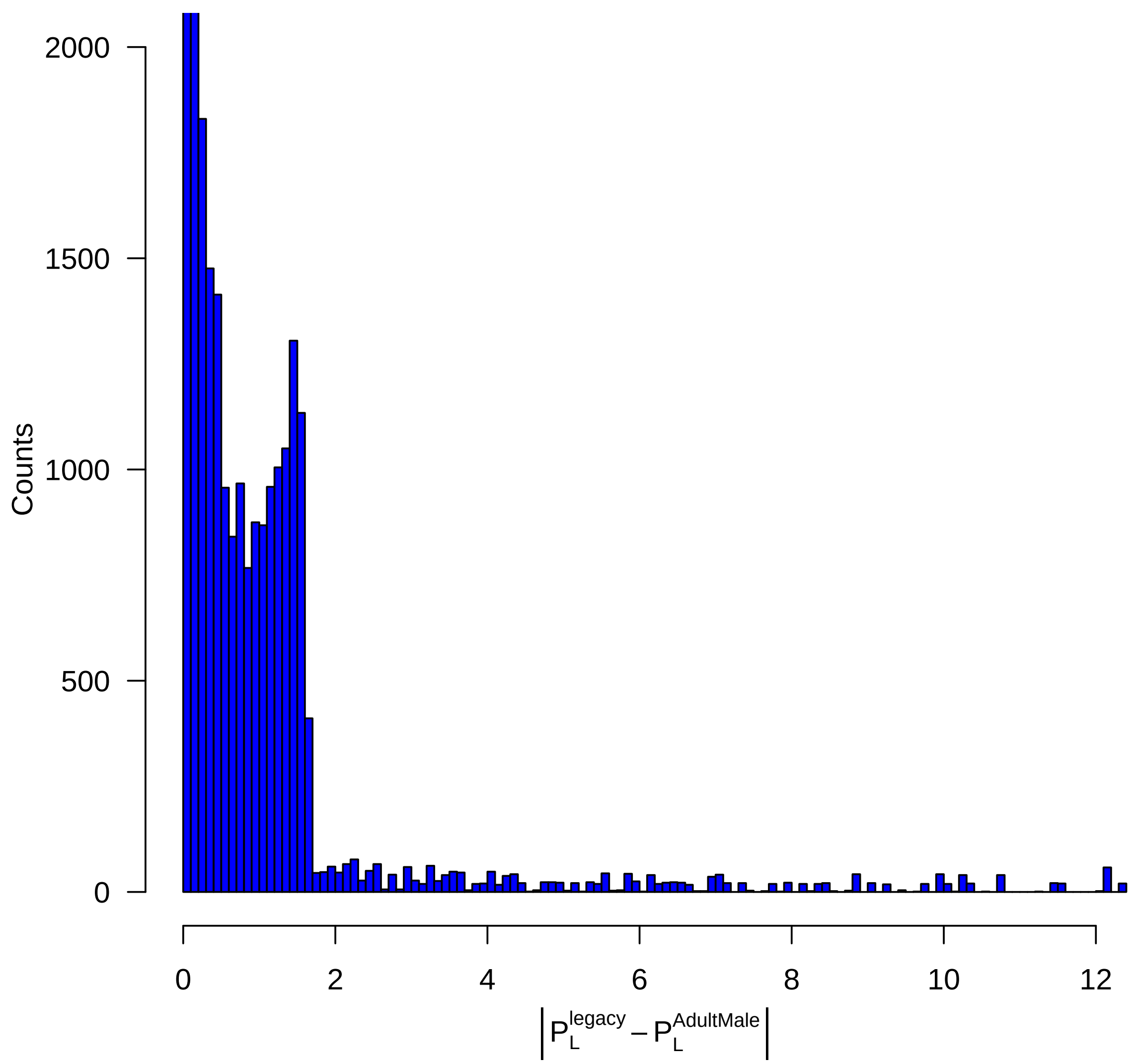

Figure 3.17: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$), protection factor 8

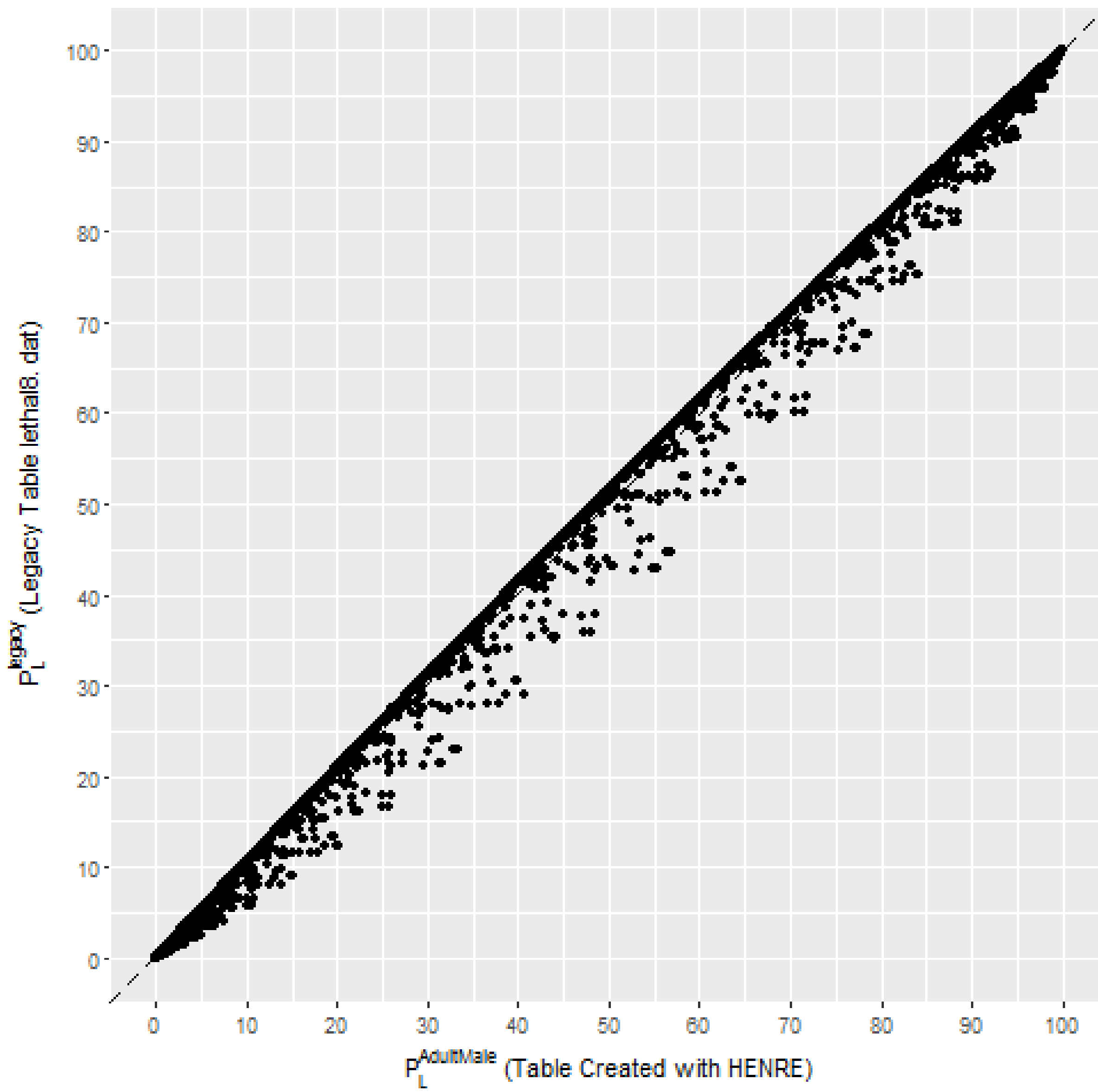

Figure 3.18: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 8

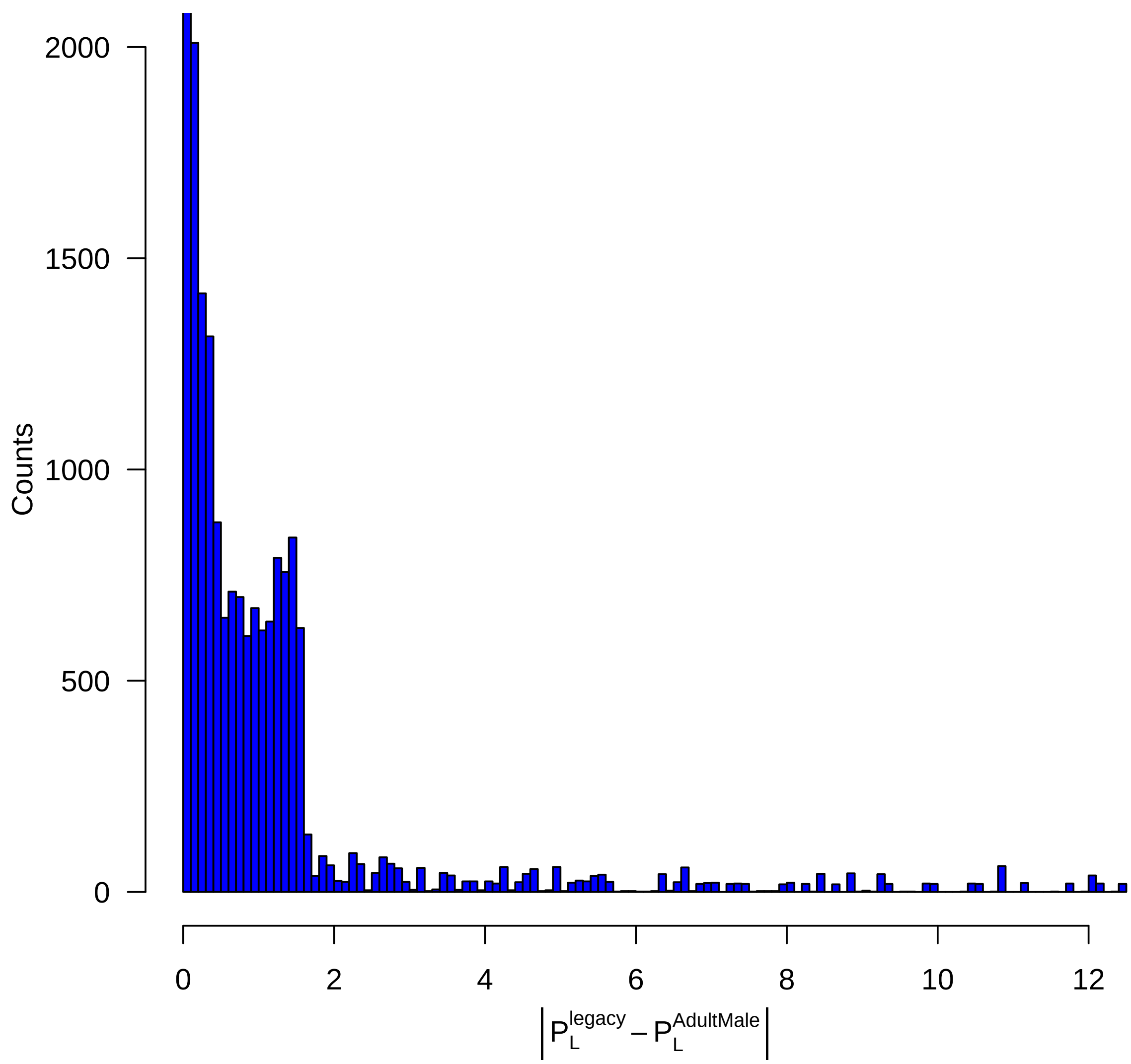

Figure 3.19: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$), protection factor 9

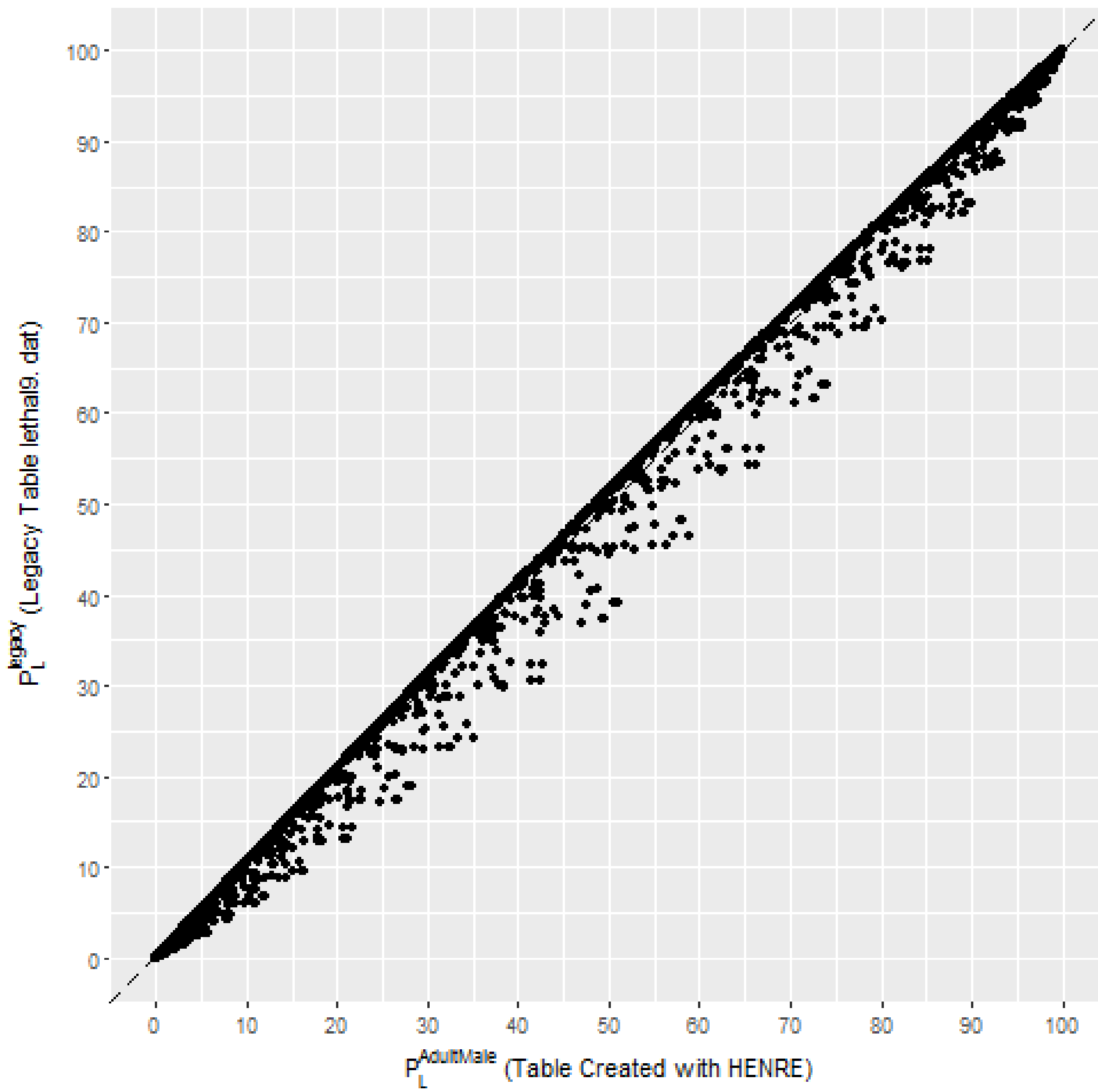

Figure 3.20: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 9

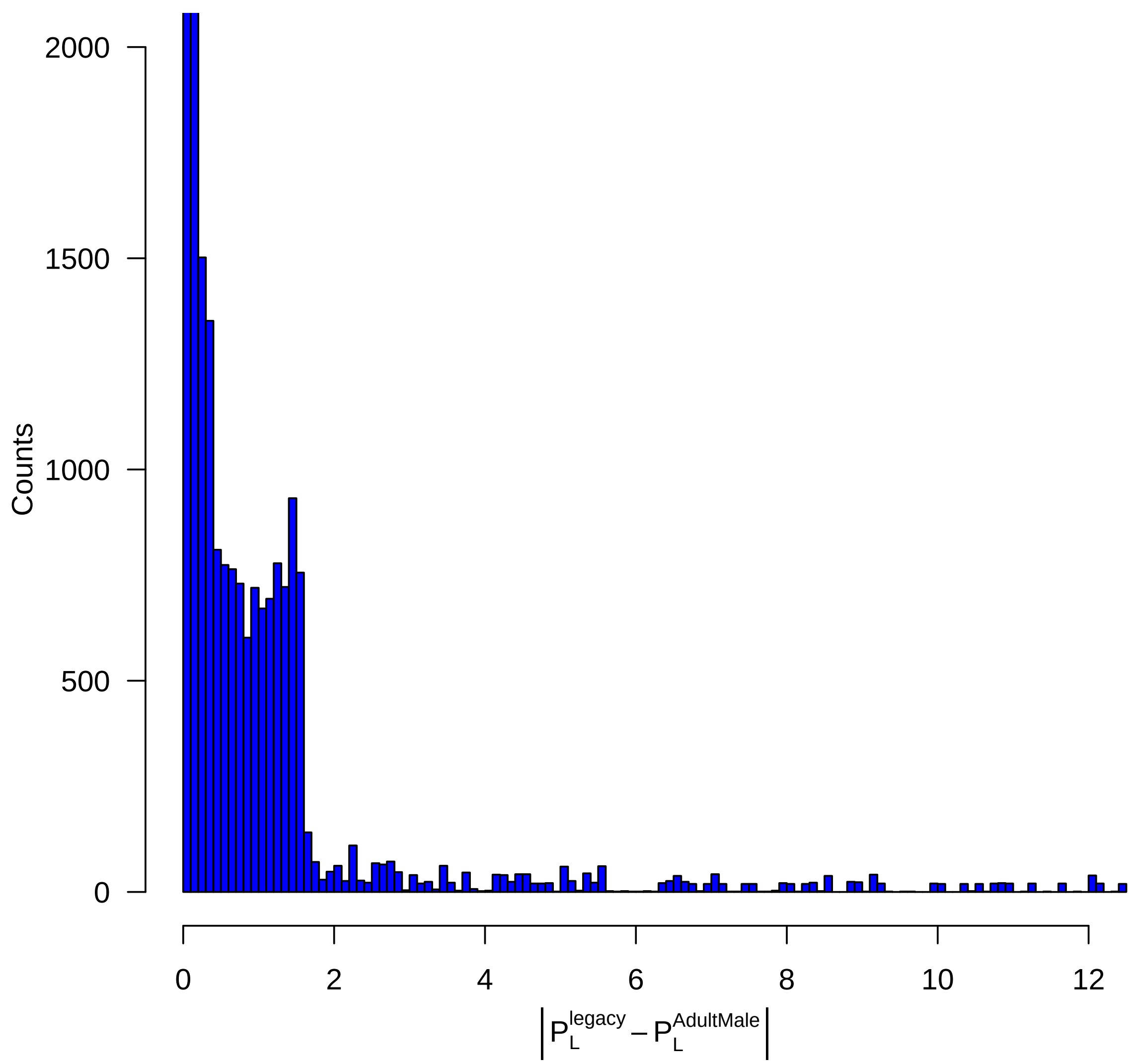

Figure 3.21: Histogram, magnitude of difference between probability of lethality given by legacy table (P_L^{legacy}) and probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$), protection factor 10

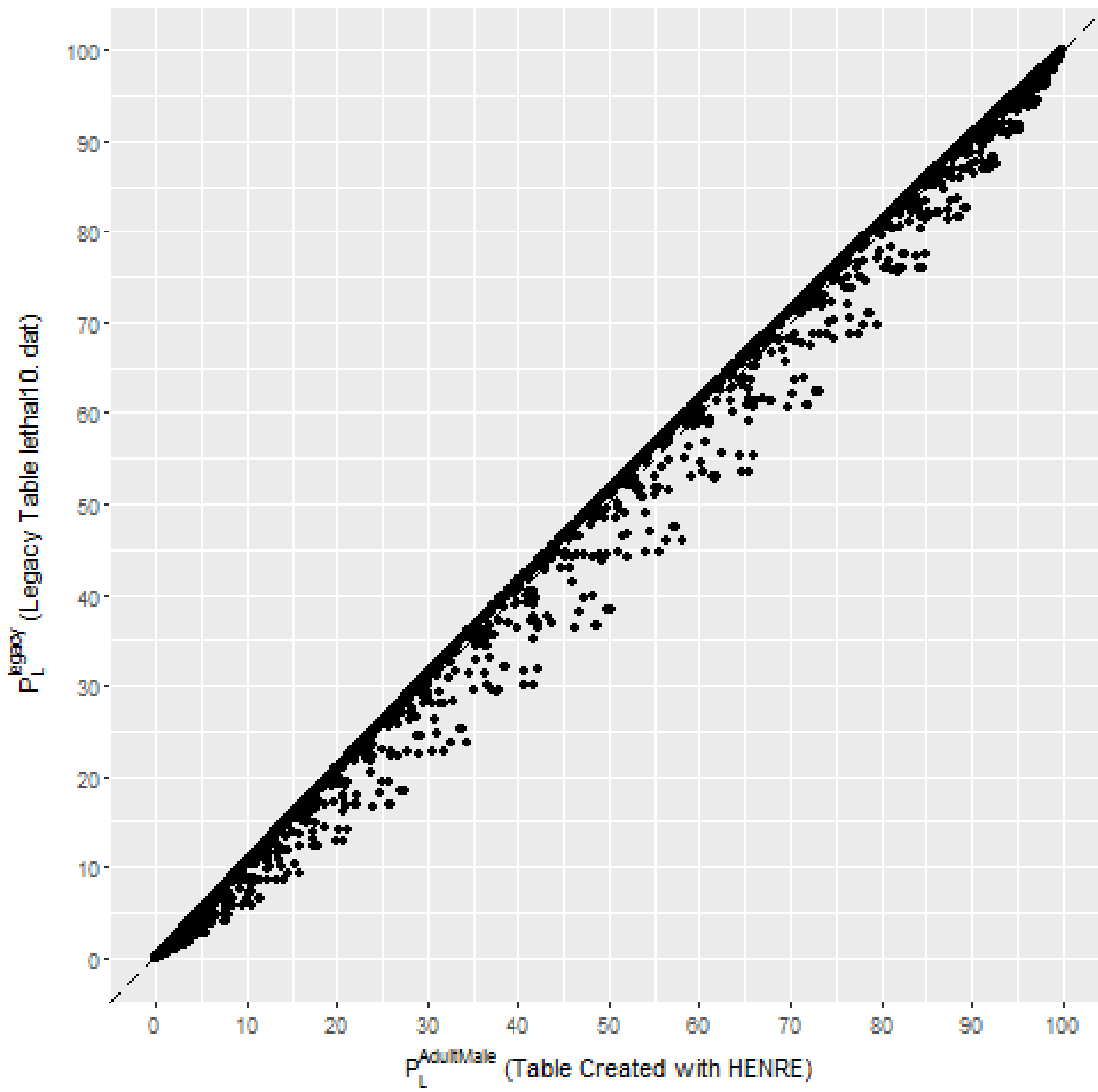

Figure 3.22: Probability of lethality given by legacy table (P_L^{legacy}) vs. probability of lethality calculated by HENRE for adult male ($P_L^{AdultMale}$) for protection factor 10

Table 3.1: Statistics for difference histograms, for protection factors 0-10. The number of rows in each table is 198,450.

Protection factor	**Difference mean**	**Difference median**	**Difference maximum**	**# with difference > 2%**	**# with difference > 5%**	**# with difference > 10%**
0	0.1389	5.31e-11	12.39	1926	993	246
1	0.1379	3.489e-11	12.4	1930	938	225
2	0.1172	2.541e-12	12.4	1930	938	225
3	0.124	5.21e-12	12.3	1948	956	263
4	0.09945	2.707e-13	12.41	1930	940	224
5	0.1111	1.245e-12	12.42	1967	978	243
6	0.1384	4.837e-11	12.3	1948	956	263
7	0.1343	1.918e-11	12.41	1931	939	224
8	0.1312	1.208e-11	12.3	1950	956	243
9	0.1081	8.367e-13	12.41	1931	939	224
10	0.1111	1.245e-12	12.42	1967	978	243

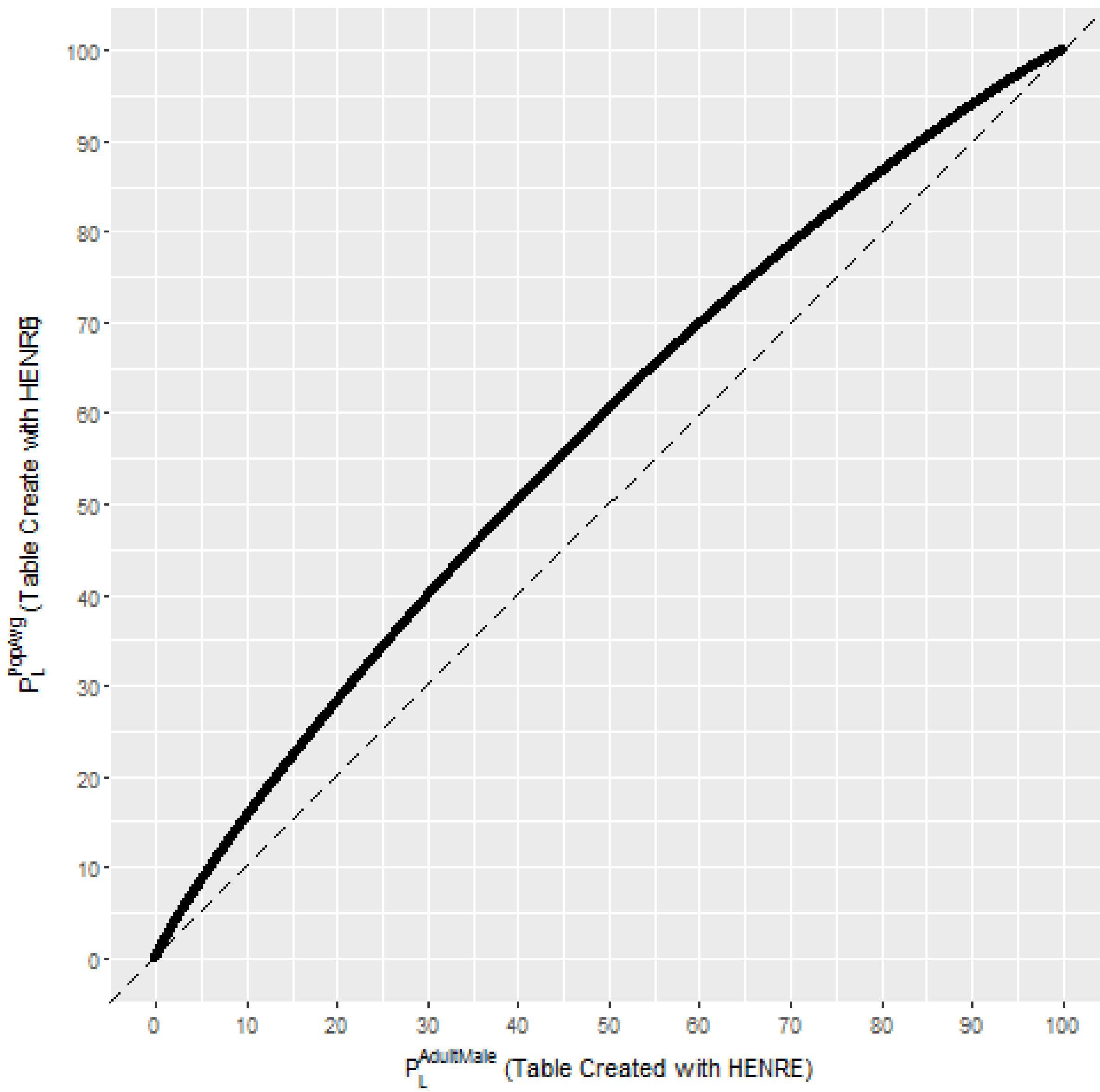

Figure 3.23: Probability of lethality calculated using HENRE: population average (P_L^{PopAvg}) vs. adult male ($P_L^{AdultMale}$) for protection factor 0

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